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Optimization of Bone Drilling Process with Multiple Performance Characteristics Using Desirability Analysis

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Abstract

In this paper the optimization of bone drilling process with multiple performance characteristics is carried out using desirability analysis. Drilling of bone is frequently done during orthopaedic surgery for the fixation of fractured parts with screws, wires or plates. The temperature and forces induced during drilling can cause damage to the bone cells which can lead to irreversible osteonecrosis resulting in prolonged healing time or loosening of the fixation. In this study, the drilling parameters, namely feed rate and spindle speed are optimized for minimum temperature and force simultaneously during bone drilling. The percentage contribution of each drilling parameter on multiple performance index is determined using analysis of variance (ANOVA). The result of the confirmation experiment shows that this approach can effectively reduce the drilling induced bone tissue injury.

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1. Introduction

Drilling of bone is commonly used in wide range of orthopaedic surgeries. A general concern during bone drilling is the thermal and the mechanical damage induced to the bone. This damage plays a very important role on the outcome of the fracture treatment process as it can cause the death of the bone cells around the drilling site termed as ostenecrosis [1-2]. The osteonecrotic cells causes loosening of the fixation leading to

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improper alignment of the broken bones, also they increase the healing time [1-2]. Therefore bone drilling with minimum damage is a major challenge for orthopaedic surgeons for proper fixation and quick healing of the damaged bones postoperatively. An investigation to optimize the bone drilling process for minimum temperature (T) and force (F) can be very helpful to reduce the drilling damage of the bone tissue.

Desirability analysis has been effectively utilized by many researchers for multiple response optimization of the machining problems [3-4]. It is based on the concept of an objective function called as desirability function to transform the response into a scale free value known as desirability. The value of the desirability ranges from 0-1 i.e. from least desirable to the most desirable respectively. The level of the factors with highest total desirability is considered to be the optimal level [3-4]. The aim of this study is to find an optimal condition of the feed rate (F) and spindle speed (S), so that the increase in bone temperature and the forces induced would be minimal simultaneously during bone drilling.

2. Experimental Details

The experiments were carried out on MTAB 3 axis Flex mill. The work material was bovine bone as human bones are not easily available and it is the closest animal bone to resemble the human bone [5]. Bones were obtained immediately after slaughtering from the local slaughter house and no animal was sacrificed specially for this research. The experiments were performed within few hours of the slaughter to maintain the physical properties of the bone [1-2]. Temperature was acquired using an Extech K-type thermocouple with data acquisition software. Kistler 9257 B piezoelectric dynamometer was used for measuring the thrust force. The experimental set up is shown in Fig. 1.

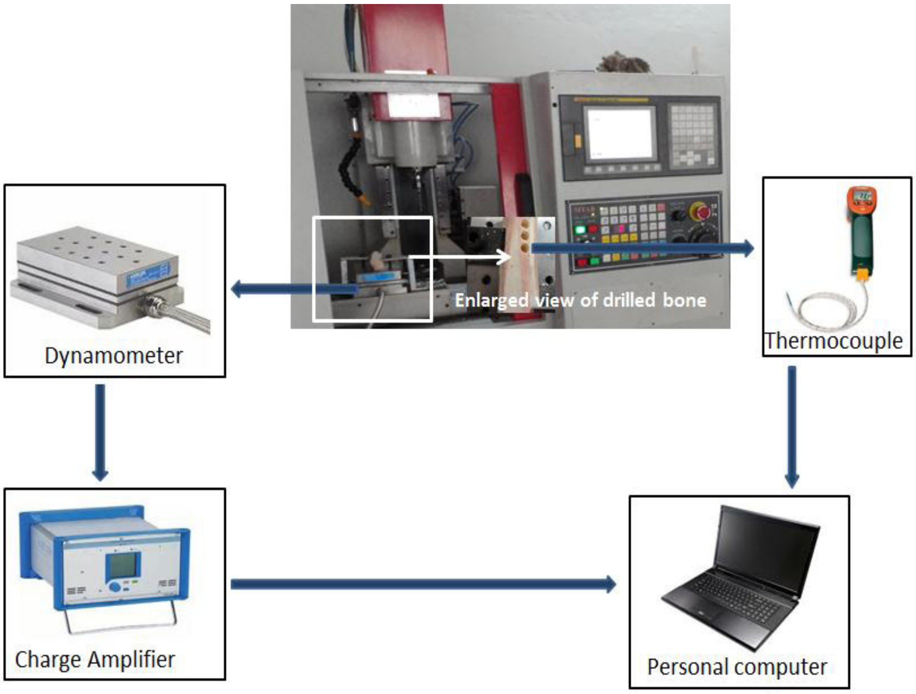

Fig. 1. Experimental set up

The bone drilling parameters considered in this study are feed rate (mm/min) and spindle speed (rpm). Three levels of each parameter have been selected and a 3^2 full factorial design is used to perform the experiments. High speed steel (HSS) drill bit of 6 mm diameter is employed without coolant to drill the bovine bone. The bone drilling parameters and their levels were selected based on the wide range of experiments reported in the literature [1-2,5-6]. The setting of the level of the parameters for each experimental trial and the obtained responses are shown in Table. 1.

3. Desirability Function Analysis (DFA)

The procedure followed to determine the optimal combination of the bone drilling parameters for multiple characteristics optimization using desirability functional analysis is discussed below.

Table 1. Experimental conditions and results

Experiment No.	Actual setting value		Temperature (°C)	Force (N)
	Feed rate (A) (mm/min)	Spindle speed (B) (rpm)		
1	40	500	45.7	12.28
2	40	1500	49.1	9.53
3	40	2500	50.7	8.01
4	50	500	44.5	19.74
5	50	1500	48.4	13.36
6	50	2500	50.1	10.14
7	60	500	46.5	30.85
8	60	1500	51.2	20.22
9	60	2500	52.6	16.30

3.1. Desirability index generation

The first step in desirability functional analysis is to compute the desirability index for each response obtained. During bone drilling minimum value of the temperature and thrust force is desirable. Therefore, smaller the better desirability function is used to calculate the desirability index of each response for every experimental trial. The desirability function d_i for smaller the better is given in equation (1)

$$d_i = \begin{cases} 1 \\ \left(\dfrac{\hat{y} - y_{max}}{y_{min} - y_{max}}\right)^r, & (y_{min} \leq y \leq y_{max}), r \geq 0 \\ 0 \end{cases} \quad (1)$$

When $\hat{y}$ is smaller than a particular criteria value the desirability is equal to 1 and if it is higher, the value of desirability is 0 [3]. Y_{min} = minimum tolerance limit of $\hat{y}$, Y_{max} = upper tolerance limit of $\hat{y}$ and r = weight to be defined by the user, considered 1 for this case [3].

3.2. Calculate the composite desirability

The individual desirability obtained for each responses are combined using equation (2) to get the composite desirability (d_C) as the performance index for multiple characteristic optimization.

$$d_C = \left(d_1^{w1} * d_2^{w2} * d_3^{w3} ....d_n^{w_n}\right)^{\frac{1}{W}} \quad (2)$$

Where, d_n = individual desirability of the response; w_n = weight assigned to the response (considered equal i.e. 0.5 for both temperature and thrust force); W = sum of the individual weights. The desirability index for each response and the composite desirability of each experimental run is given in the Table 2. Higher the value of the composite desirability represents that the corresponding experimental result is closer to the ideally normalized value [3-4].

Table. 2. Individual and composite desirability

Experiment No.	Individual desirability (d_i)		Composite desirability (d_C)
	Temperature (°C)	Force (N)	
1	0.851852	0.813047	0.832223
2	0.432099	0.93345	0.635093
3	0.234568	1	0.484322
4	1	0.486427	0.697443
5	0.518519	0.765762	0.630128
6	0.308642	0.906743	0.529017
7	0.753086	0	0
8	0.17284	0.465412	0.283622
9	0	0.63704	0

Table. 3. ANOVA results for composite desirability

Parameter	DOF	SS	V	F value	P (%)
A	2	0.58506	0.29253	17.37	81.94
B	2	0.06153	0.03076	1.83	8.62
Error	4	0.06735	0.01684		9.433
Total	8	0.71394			100

Where, DOF = Degree of freedom, SS = Sum of squares, V= Variance, P= Percent contribution

3.3. ANOVA

The percentage contribution of each factor on the d_C is determined by analysis of variance (ANOVA). The Fisher's F-test analysis is also used to find the change in which parameter significantly influences the d_C . Higher the F-value shows that the parameter has more strong influence on the multiple performance index. The result of the ANOVA analysis and the F-values are listed in Table 3. The percentage contribution of each factor is shown in the last column of the Table 3.

4. Results and discussion

From the Table 2 it is clear that the highest composite desirability (d_C) is obtained for the experiment number 1 and is the optimal level of the feed rate and spindle speed during bone drilling for minimizing the temperature and thrust force simultaneously. The results from the F-test and ANOVA analysis clearly suggests that the feed rate has the highest influence and contribution to the d_C .

For the validation of the results obtained from DFA the confirmation test is carried out. The predicted $\hat{d}_C$ for the optimal combination of the parameters A1B1 is calculated from the equation (3).

$$\hat{d}_C = d_{cm} + \sum_{i=1}^{k} (\bar{d}_{ci} - d_{cm}) \tag{3}$$

Where $\hat{d}_C$ = estimated composite desirability, d_{cm} = total mean composite desirability, $\bar{d}_{ci}$ = the mean value of the composite desirability at the optimal level and k = the number of parameters affecting the multiple performance characteristics. The confirmation results are shown in Table 4. The composite desirability predicted for the optimal level i.e A1B1 is 0.7058 and that obtained from the experimental analysis is 0.8322. Thus, a gain in the d_C is obtained which clearly specifies that the use of desirability based approach can be very effective to minimize the injury to the bone tissue during drilling.

Table 4. Confirmation experiment result

	Optimal process parameters	
	Predicted	Experimented
Level	A1B1	A1B1
d_C	0.7058	0.8322

5. Conclusions

Experiments are conducted on bovine bone with different combinations of the feed rate and spindle speed to optimize their levels for minimum temperature and force during drilling. The conclusions obtained from the above DFA analysis are given below:

1. The investigation with feed rate 40mm/min and spindle speed 500rpm has the highest composite desirability and is recommended parameters setting for minimization of temperature and thrust force during bone drilling.
2. From the ANOVA results it is found that the feed rate has the highest contribution (81.94%) to the multiple performance index i.e composite desirability.
3. Confirmation test performed shows that the DFA approach is suitable to minimize the bone tissue injury during drilling.
4. This approach will simplify the tedious task of multiple objective optimization of bone drilling process and will facilitate the orthopaedic surgeons to perform bone drilling with minimum damage.

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